A METHOD FOR COLLECTION AND EVALUATION OF TURBINE PERFORMANCE TEST DATA

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ABSTRACT

The goal of an effective turbine cycle performance testing program is to locate and quantify degradation within the turbine cycle. To achieve this goal it is necessary to collect and analyze data that is both accurate and repeatable. For accuracy, calibrated test grade instrumentation, as specified in the ASME Performance Test Codes, must be used in all critical locations. For repeatability, consistent calibration procedures, plant set up and analytical methods, in addition to quality instrumentation, are required. Santee Cooper has developed a performance testing program that has, through continuous research and development, evolved into a useful tool for the evaluation of turbine cycle performance.

Winyah Unit 1, a 300 Mwe General Electric unit, is used as a platform to detail the current state of the Santee Cooper testing program. Items to be discussed include instrument selection, calibration, data acquisition systems, field data manipulation, data analysis, and diagnosis. Data trends over a two year period will be analyzed, with special attention paid to data verification. Finally, planned enhancements to the performance testing program will be presented.

INTRODUCTION

The intent of this paper is to present the current state of the Santee Cooper performance testing program in a manner which will provide guidance in setting up a new testing program or provide ideas for modification to an existing program. We have included discussions on instrumentation, data acquisition and data analysis with specific examples from one of our recent tests. As the final section (Future Plans) indicates, our performance testing program is not static, and it is not our intent to present this paper as the final word in performance testing. We do think, however, that others can benefit from our experience. The references noted in the appendix provide detailed guidance on specific aspects of performance testing and test data analysis and should be referred to when applying the methods of this paper to a specific generating unit.

UNCERTAINTY ANALYSIS

The first step in developing a performance test program is identifying the desired results and the accuracy required to achieve these results. Once you have identified this end goal, the required instrumentation accuracy can be determined through an uncertainty analysis.

Detailed uncertainty calculations (Reference 4) for an entire performance test would be a tedious task if performed by hand. By using PEPSE to perform individual sensitivity calculations we have simplified the process considerably and are able to look at the system wide effects of a change in a single data point. A PEPSE model of Winyah 1, utilizing Type 8 turbines and GE design data, was the basis for the sensitivity model. Next, each test data point was decreased by 1 percent. A percent change in an output parameter per unit change in input parameter could then be easily calculated. Table 1 shows the effect of changes in various data points on heat rate. Although all of the input parameters indeed have an effect on heat rate, throttle flow and generation make up 99.6 percent of the resultant heat rate uncertainty. This analysis, therefore, provides the basis to determine required instrument accuracy and pinpoints the key locations that require special attention during the test.

TABLE 1 -- HEAT RATE UNCERTAINTY

PARAMETER	MEASUREMENT UNCERTAINTY	HEAT RATE SENSITIVITY	HEAT RATE UNCERTAINTY
THRTL FLOW	1.61 %	1.00 %/%	1.61 %
GENERATION	0.80 Kw	1.01 %/Kw	0.81 %
THRTL PRESS	2.00 PSI	0.00 %/PSI	0.01 %
THRTL TEMP	1.00 F	0.06 %/F	0.06 %
COLD RH PRESS	1.75 PSI	0.01 %/PSI	0.01 %
COLD RH TEMP	1.00 F	0.05 %/F	0.05 %
HOT RH TEMP	1.00 F	0.04 %/F	0.04 %
#5 FW OUT TEMP	1.00 F	0.02 %/F	0.02 %
#6 FW OUT TEMP	1.00 F	0.12 %/F	0.12 %
	RESULTANT HEAT RATE UNCERTAINTY = 1.81 %		

INSTRUMENTATION

The critical test data locations identified in the uncertainty analysis will receive the emphasis during instrumentation selection. Looking at the results in Table 1, the most significant effect on heat rate uncertainty is the throttle flow measurement. Therefore, an accurate method for flow measurement needs to be considered. At Winyah this has resulted in the purchase of calibrated condensate flow tubes. In addition, our uncertainty analysis indicates that temperature inaccuracies cause greater errors than pressure inaccuracies. This has led to an effort to improve temperature measurement accuracy through the use of calibrated four wire RTD's.

Temperature Measurement

Initially, calibrated type E thermocouples were used for temperature measurements during performance tests, but several problems existed. First, thermocouples had a tendency to drift over a short period of time, causing concern when a time lag existed between test set up and actual testing. Second, long lead lines from the thermocouple to the data logging system added another source of error. Even if a lead line correction is applied, the constantly changing environment can cause a significant error when compared to the small signal. Finally, cold junction compensation adds an additional source of error to the system. The advantages of thermocouples are low cost and durability. If an inexpensive temperature measurement is required and high accuracy is not necessary, thermocouples are a good choice.

RTD's offer the advantages of very high accuracy (in the $0.1^{\circ}F$ range), a lesser tendency to drift, no lead line corrections and a much stronger signal. The disadvantages of RTD's are that they are more fragile than thermocouples and much more expensive. During the November 1988 Winyah 1 performance test, calibrated RTD's were used exclusively for temperature measurement. Throughout the test, the RTD's performed very well at temperatures below $650^{\circ}F$. However, after extended time periods at $1000^{\circ}F$ the RTD's began to drift, then exhibited an open circuit failure. After further testing of the RTD's and discussions with the manufacturer, it was concluded that contaminated ceramics reacted with the platinum sensing element to cause the drift and failure experienced. Through extensive testing, we have found that RTD reliability at $1000^{\circ}F$ is difficult to obtain. RTD's from several manufacturers are currently being evaluated to find an acceptable solution to the problem.

Because RTD drift is a function of temperature excursion, all of our RTD's are now being segregated based on measurement temperature. For example, the continuous lead RTD's for cooling tower testing are calibrated to 200°F, and the RTD's for performance tests are calibrated to two ranges, one group for measuring temperatures below 500°F and one group for temperatures exceeding 500°F. A three point calibration is used for each temperature group. A one year calibration schedule is planned, however, that may change based on the results of spot calibration checks. The development of a standards lab for in house calibrations will be helpful in determining a reasonable calibration schedule.

Pressure Measurement

Pressure measurements are important not only for enthalpy calculations, but also for use as a diagnostic tool. First stage pressure trends are often used as an indication of high pressure turbine conditions, in addition to being an indication of main steam flow. Pressures elsewhere in the cycle can also be used as an indication of flow downstream of the pressure location. Although they do not have as strong an effect on heat rate, pressure measurements are typically more reliable than temperature measurements. If an inconsistent data point is discovered after it is too late to repeat the test, the temperature will likely be adjusted to bring the test data in line. For these reasons, high accuracy pressure measurements are a must.

We are currently using a combination of Rosemount 1151 and L&N 2360 pressure transmitters, both of which are in the 0.25 percent error class. Recently, we began testing Statham 8000 series pressure transmitters because of the advantages of a non-interactive span, for easier calibration, and because of interchangeable electronics which help support a large variety of pressure ranges. Another advantage of the Statham transmitter is the elimination of the static pressure correction required by the Rosemounts for differential pressure transmitters.

All of our pressure transmitters are calibrated using a precision deadweight tester that is National Bureau of Standards traceable. Critical transmitters, those that impact test uncertainty most significantly, are first calibrated in the Performance Lab, and then transported to the test site and put in location for temperature saturation. After a 24 hour minimum soak time, the transmitters are calibration checked and adjusted as needed. After the test is complete, the transmitters are removed and an "as found" calibration is recorded. This method minimizes the opportunity for significant drift to occur without detection.

Standard pressure ranges are being established for all non-critical pressure transmitters. For example, a 0 to 500 psig calibration for all pressure transmitters installed on the low pressure feedwater train will not cause a significant impact on the uncertainty of turbine efficiencies or heat rate, and this pressure range will allow us to instrument any of our nine units without recalibration. Other standard pressure ranges will be set up for the high pressure feedwater train, extractions, and the balance of the non-critical pressure locations. This will also allow pressure transmitters to be put on a long term calibration schedule to aid in life extension of the instruments.

DATA ACQUISITION

A Daytronics System 10 data logger is currently being used to retrieve data from test instrumentation. The Daytronics allows plant locations and graphic set ups to be saved to a floppy disc, so once developed, each unit specific set up can be saved for the next test. Graphics capabilities of the Daytronics allow unit parameters to be monitored throughout the test for stability checks.

To minimize overall uncertainty in pressure measurement, data logger pressure channels are calibrated in a loop with the pressure transmitters. RTD channels are calibrated to a specific range using a precision shunt box. For example, main steam temperature is calibrated at 750°F and 1000°F. Other RTD channels will be calibrated to a range appropriate to the temperatures that are expected on that channel.

Once a scan of data is retrieved by the Daytronics unit, the data can be stored in a number of ways. Data can be directly stored on a PC, but this occupies the PC for the entire test time. An external mass storage device, such as a Techtran, can be used, allowing the use of the PC throughout the test. This is the method that we presently use. The third alternative is the use of Daytronics history cards, which provide four internal memory registers and allow continuous data logging even when uploading data. This allows constant hookup between the PC and Daytronics, but still allows the PC to be used for other tasks. We are in the process of purchasing the necessary Daytronics History cards to simplify the process of data acquisition.

After the test is completed, we use a Compaq III portable micro computer for data manipulation and analysis. The Compaq III is used for communications to the Daytronics data logger and to our IBM mainframe computer, data averaging, data verification and transferring raw test data into a PEPSE input deck.

Several software packages, both commercial and internally developed, are used in the course of our test data collection and analysis. The commercial packages are general in nature and any number of similar packages would probably be adequate. The internally developed software was developed for a specific need that could not be filled with a commercial package. If a commercial package is available, it is generally more productive and cost effective to purchase software than to develop it. Three of the five commercial software packages are used for communications. These are:

ProComm - communicates between the Compaq and the Techtran mass storage device.

Utilipac - communicates between the Daytronics and the Compaq PC.

IBM 3270 Control Program - communicates between the Compaq PC and the IBM mainframe.

The other two commercial programs that are used, PEPSE (Performance Evaluation of Power System Efficiencies) and Lotus, form the heart of the test data analysis. PEPSE is an iterative heat balance program which is used for modeling the turbine generator cycle in the plants. Lotus is used for a variety of tasks, such as graphing and making calibration corrections. The flexible programing features of Lotus also make it an ideal basis for specialty software that requires frequent changes. Lotus is used as the framework for our internally developed "AUTOLOAD" worksheet.

AUTOLOAD was designed to decrease data handling time and eliminate errors associated with manually typing large amounts of data into a PEPSE deck. Instead of reading pressure and temperature values from a printout, applying corrections by hand and then manually entering the corrected data into PEPSE, the computer was employed to do these tasks. AUTOLOAD performs the following steps of the test data manipulation process:

(1) retrieve the averaged test data from an ASCII file,
(2) apply RTD corrections to temperature measurements,
(3) apply water leg corrections to pressure measurements,
(4) apply barometric pressure corrections to pressure measurements,
(5) average multiple data points (i.e. redundant temperatures),
(6) input test data into a PEPSE format input deck, and,
(7) output the PEPSE deck to a file for processing.

The program is very simple to use, yet still remains flexible enough to allow changes in the field.

DATA ANALYSIS

Data analysis at Santee Cooper is performed in three segments that we have designated level 1, level 2 and level 3. Level 1 consists of field data verification and analysis in a PEPSE test data reduction model. Level 2 employs the turbine cycle characteristics calculated from the level 1 analysis and corrects the test data to design boundary conditions. Level 3 is a comparison of the current cycle operating conditions to benchmark conditions. The following discussions detail the specific features of each level in our analysis procedure.

Level 1

The main goal of level 1 analysis is to determine the absolute condition of the turbine cycle at the present time and assure that the data used in this determination is correct. A verified PEPSE test data model is necessary before the analysis begins and should be based a design model that agrees with vendor heat balances. "PEPSE Manual Volume III -- Applications Manual" (Reference 1) provides guidance for the set up and validation of the design model. Standard turbines are then replaced by PEPSE Type 8 turbines. Extraction pressure drops are commented out and operations are set up to calculate extraction pressure drops based on turbine extraction pressure and corresponding feedwater heater bleed (shell) pressures. These calculated pressure drops are used as an additional verification item and are output using the Special Output Processor. Straight expansion lines are used from the HP turbine inlet to the cold reheat, and from hot reheat to crossover. For feedwater heaters, feedwater outlet temperature and pressure, bleed pressure and drain outlet temperature are specified using the special input processor. Feedwater inlet pressures, though measured, are input only in cases where elevation pressure changes are significant, and are used more as an instrument consistency check. Generation is input and PEPSE's Special Option 2 is used to determine the inlet and outlet state points of the LP turbine sections that operate in the two phase region. Feedwater flow is calculated from differential pressure inputs obtained from the final feedwater flow device.

Before beginning a detailed analysis on the test data, a thorough data verification process must be completed. The purpose of this step is to avoid spending a lengthy time analyzing test data, only to find out that some suspicious test data exists. By field verifying the test data you can often locate the source of a "bad" test data reading and correct the problem, or alternatively, after verifying your test equipment you can collect additional data to replicate your findings. Several steps are included in the test data verification process, with the first being a spot check.

Again putting the uncertainty analysis to use, the parameters requiring frequent spot checks are selected. As a rule, look closely at all parameters used in the heat rate calculation and in the HP and IP efficiency calculation. Using an old test report as a template, look at these data points and confirm that the measured values are of the right order of magnitude. If no erroneous values are found, a more detailed look at the redundant measurements is in order.

To assure maximum accuracy of test results, redundant instrumentation is used at all critical test locations. Output from the redundant instruments can be plotted and compared to determine if any significant instrument drift occurs over the course of several days testing. For example, at Winyah Unit 1, the accuracy of throttle temperature has a significant effect on the calculated value of HP turbine efficiency. A $1^{O}F$ error in throttle temperature corresponds to a 0.34 percent error in calculated HP turbine efficiency. To assure an accurate measurement of throttle temperature, outputs from three calibrated RTD's are averaged. The throttle temperature scans for each RTD are graphed vs. time, as depicted in Figure 1. Here the average throttle temperatures are used for clarity, however, to detect more gradual drifts, plot each temperature scan for the RTD's and compare trends. In Figure 1, the temperature measurements track well for tests one through four, however, the throttle south #2 RTD drifted prior to or during test five. After verification that the instrument is incorrect (i.e. calibration check at ice point), this temperature will be removed from the average for all tests.

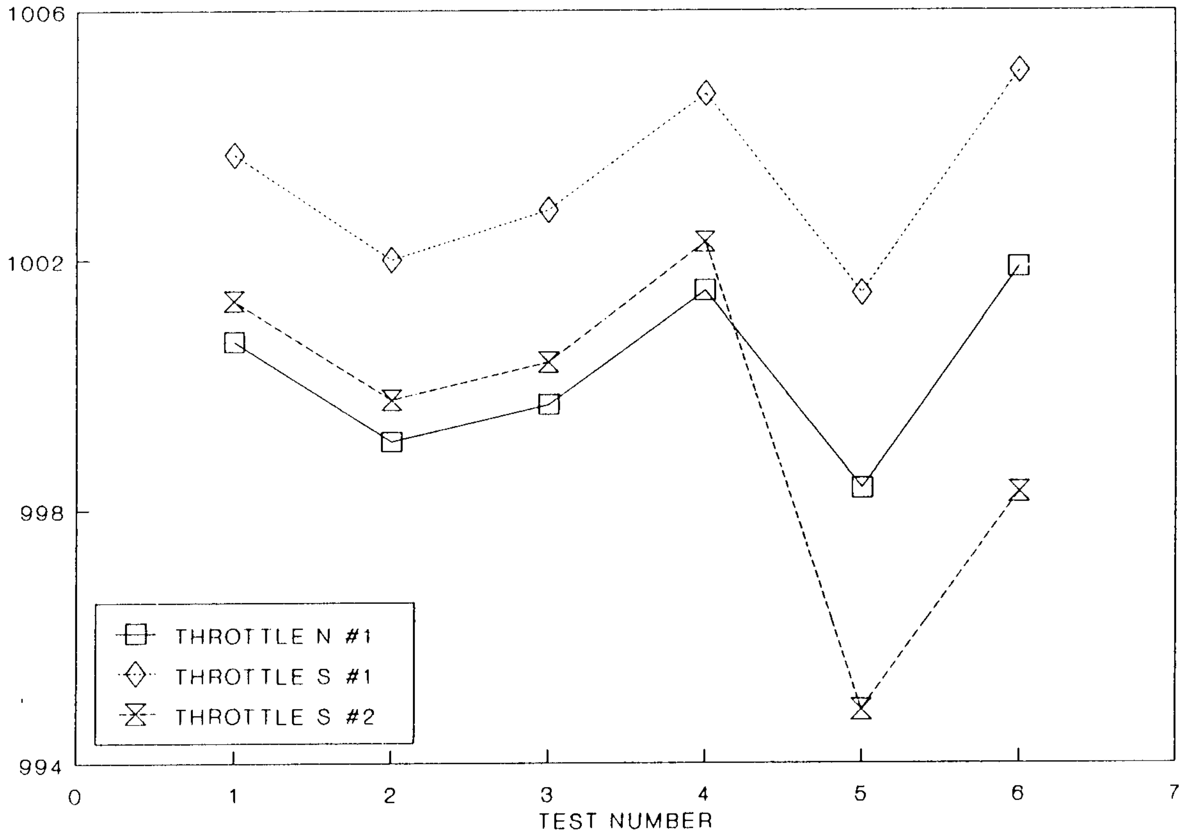

FIGURE 1 -- THROTTLE TEMPERATURE vs. TEST NUMBER

Redundant instrumentation is also used to measure the following critical data points: throttle pressure, throttle temperature, first stage pressure, cold reheat pressure, cold reheat temperature, hot reheat pressure, hot reheat temperature, crossover pressure, crossover temperature, condenser pressure and #6 feedwater heater outlet temperature. Figure 2 is a unit schematic of Winyah 1 depicting all

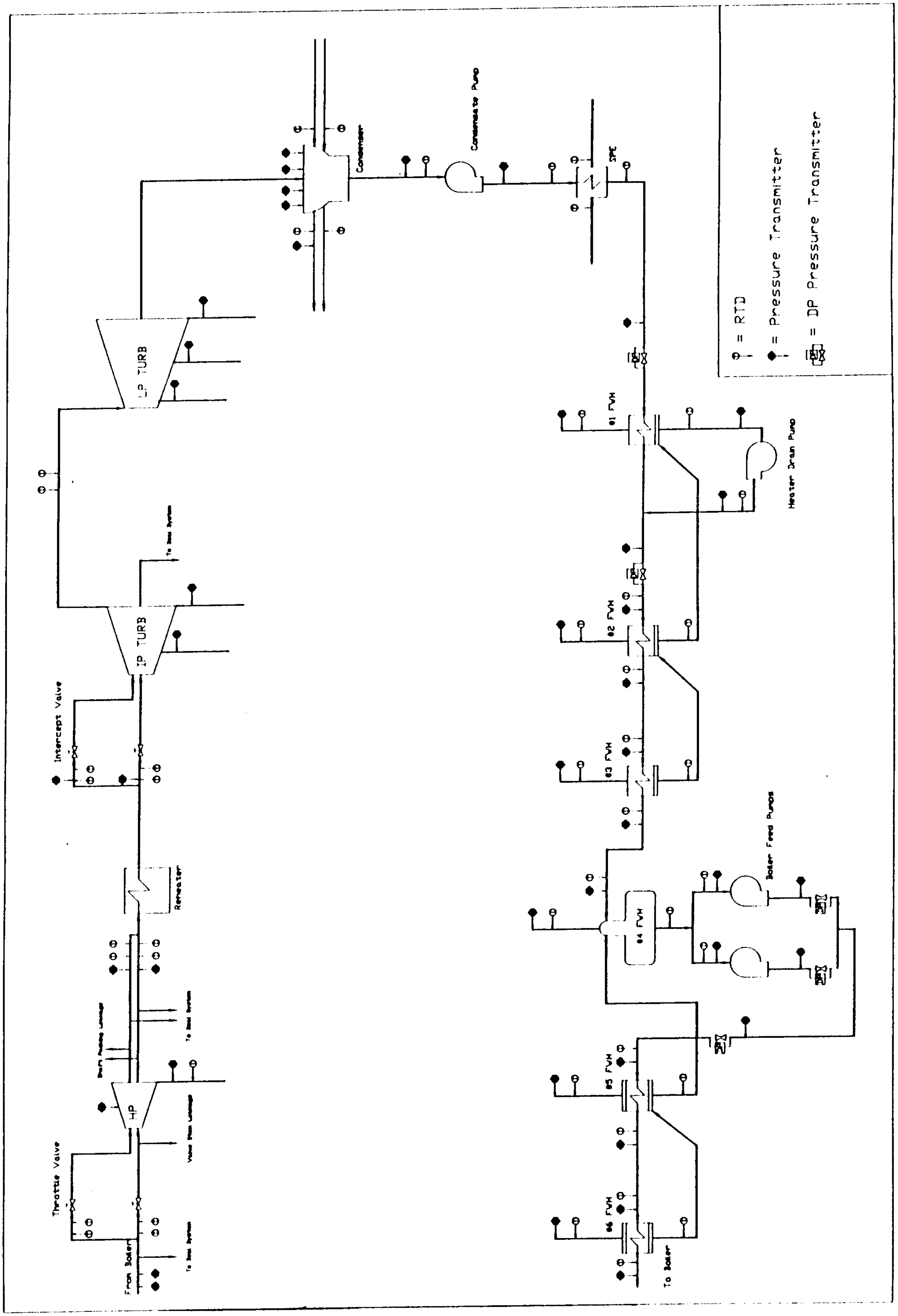

FIGURE 2 -- INSTRUMENTATION DIAGRAM

of the test instrument locations. Note the redundant instrumentation locations as listed above. Once any discrepancies discovered during the redundant instrumentation checks are resolved the test data can be reconciled.

Test data reconciliation (Reference 5) consists of quantifying losses in the turbine cycle, either as lost generation or increased heat rate, then locating the cause of the losses. The purpose of the reconciliation is two fold. First, by locating and quantifying the losses on an individual basis, all significant losses can be accounted for. Second, if the sum of the individual losses exceeds the total measured loss, incorrect test data is indicated.

TABLE 2 -- RECONCILIATION DATA

PARAMETER	10/86	11/88	CHANGE 10/86-11/88
GENERATION	295 Mw	287 Mw	-2.51 %
HP EFFICIENCY	83.3 %	80.4 %	-3.61 %
IP EFFICIENCY	91.2 %	91.6 %	+0.44 %
MAIN STEAM FLOW	1926 klb/hr	1934 klb/hr	+0.43 %
1st STAGE PRESS	1885.7 PSI	1915.2 PSI	+1.54 %
CRH PRESS	563.0 PSI	555.6 PSI	-1.33 %
HRH PRESS	512.9 PSI	506.1 PSI	-1.34 %
CROSS OVER PRESS	124.9 PSI	123.2 PSI	-2.19 %
COND PRESS	2.0 PSI	2.0 PSI	0.00 %

To reconcile test data, a benchmark data set is necessary. This benchmark could be a prior performance test or an ASME acceptance test, but the intent is that the benchmark be representative of the best operating condition of the unit. Next, the changes in several parameters need to be quantified. For illustration purposes, we will use the Winyah November 1988 test data, shown in Table 2. The test results indicate that generation decreased 2.5 percent over a two year period, HP turbine efficiency decreased by 3.6 percent, condenser pressure was constant at 2.0 inches Hga and both main steam flow and IP turbine efficiency increased slightly. Since no maintenance was performed on the IP turbine between the two tests, we can be sure that the efficiency did not actually increase. Most likely the calculated efficiency increase results from an unaccounted for increase in N2 packing leakage (Reference 7).

A good rule of thumb for the HP and IP turbines is that approximately 28 percent of generation is developed by the HP section and approximately 25 percent comes from the IP section. These percentages can be calculated more closely from the vendor heat balance, however, these approximations are typically very close. A one percent change in flow corresponds to approximately 0.94 percent change in output when exhaust losses are considered and condenser back pressure is constant. Calculating the individual losses and summing yields:

HP turbine efficiency: (0.28) * (-3.60%) = -1.00 %
IP turbine efficiency: (0.25) * (+0.44%) = +0.11 %
Flow: (0.94) * (+0.43%) = +0.40 %
Total loss: -0.49 %

Again, since the IP efficiency could not have actually increased, it should not be included in the reconciliation. This yields a total loss of 0.60 percent, which only accounts for 23 percent of the total generation loss. Looking closer at the data in Table 2, notice that although the main steam flow appears to have increased from the benchmark test, the pressures downstream of the first stage have decreased by approximately 1.3 percent. This indicates that the flow has actually decreased. Using a 1.3 percent decrease in throttle flow in the reconciliation, a total loss of 2.27 percent is calculated, providing a 90 percent reconciliation. After a satisfactory reconciliation, level 2 analysis can begin.

Level 2

Level 2 analysis corrects test data (specifically controllable parameters) back to design conditions. The results of this analysis tell how well the machine, in it's current condition, would perform if all boundary conditions were at design values. The boundary conditions considered are main steam temperature, main steam pressure, hot reheat temperature, condenser pressure and feedwater heater TTD's and DCA's. The final PEPSE model from the level 1 analysis is the basis for the level 2 model.

PEPSE's special output processor provides ready access level 1 information needed for the level 2 analysis. The information needed includes:

1.) turbine stage efficiencies,
2.) turbine stage pressure ratios,
3.) turbine stage flow coefficients,
4.) extraction pressure drops,
5.) main steam temperature,
6.) main steam pressure,
7.) reheat steam pressures,
8.) condenser pressure,
9.) feedwater heater TTD's and DCA's, and,
10.) throttle valve reference conditions.

Efficiency and pressure ratio or efficiency and flow coefficient calculated during the level 1 analysis are used as inputs for PEPSE's type 8 turbines. Throttle valve reference conditions are input, as well as Type 2 streams with the pressure drops calculated from the level 1 analysis. Finally, all of the boundary conditions from the test are input and Special Option 1, which calculates main steam flow for a fixed control valve position, is flagged. In this manner, the first level 2 analysis PEPSE run should exactly match the final level

1 run and provide a good verification of the level 2 input deck. To complete the analysis, the design values for controllable losses are successively input using PEPSE's special input processor until all of the controllable parameters are at design conditions. The results can then be used for a controllable loss economic analysis.

The economic analysis considers changes in turbine heat rate for each parameter that deviates from design conditions. To translate this into a dollar value we need current values for boiler efficiency, fuel cost, capacity factor and availability. At Santee Cooper, average values are used for these parameters, providing a constant standard for system wide comparison. The relative cost of an off design controllable parameter is then calculated as follows:

$$\text{Annual Cost} = \frac{\text{Fuel Cost}}{\text{Boiler Eff}} * \text{Gen} * C_f * \text{Aval} * (HR_t - HR_d) * 8760\ \text{hr/yr}$$

Where:
C_f = capacity factor
Gen = generation as tested
Aval = availability
HR_t = heat rate as tested
HR_d = heat rate at design

To simplify the analysis, PEPSE's save case feature and operations are used to calculate the cost of off design operation. This is done by saving the turbine heat rate in an operational variable storage location for each case. These stored heat rate values are carried forward to the last (standard) case in the level 2 analysis. Here the heat rate changes for each parameter are calculated, and the associated annual cost is calculated. Heat rate and cost are output using the special output processor. Finally, with the model corrected to standard boundary conditions we can move on to the level 3 analysis.

Level 3

Level 3 analysis compares the current mechanical condition of the turbines and feedwater heaters to a previously determined condition, typically from a benchmark test. Level 3 analysis is performed in the same manner as level 2, except that component performance parameters are successively inserted, as opposed to controllable parameters. The HP turbine efficiency, IP turbine efficiency, LP turbine efficiency, LP heater TTD's and DCA's and HP heater TTD's and DCA's are the compared to the benchmark data. The HP and LP heaters are grouped since the effect of the heaters on overall cycle performance is fairly small. The economic analysis for level 3 is again implemented using PEPSE's save case and operations as outlined in the previous section, completing the test data analysis.

FUTURE PROGRAM PLANS

The Santee Cooper performance testing program continues to grow and improve. Major improvements in instrument accuracy are the top priority. Two items currently in progress are the development a standards lab and the procurement of a highly accurate condensate flow measurement device.

Condensate Flow Measurement

The largest contributor to measurement uncertainty at all Santee Cooper units is the main steam flow measurement. The original welded venturi downstream of the boiler feed pump offers no access for inspection or accurate calibration. To improve this situation, high head recovery flow tubes, designed with the same elliptical approach as an ASME PTC 6 flow nozzle, were ordered for installation in the low pressure condensate pipe. Flow tubes were selected instead of PTC 6 nozzles because the cost is much lower and they can be calibrated to the 0.25 percent uncertainty required by ASME PTC 6 nozzles. It should be noted that flow tubes are not currently ASME approved for acceptance testing and if any acceptance tests are anticipated a PTC 6 throat tap nozzle should be selected.

Standards Lab

To further improve test program quality, both primary and secondary standards labs are being developed. The labs will be equipped to perform a full range of calibration for temperature devices, field electrical measurement devices and data logging equipment.

The primary lab will utilize two Rosemount International Defining Standards to calibrate test RTD's. Stability of the standards is $\pm 0.01^{\circ}$C per year. To calibrate the standards a precision ice bath circulator with a controller accuracy of $\pm 0.005^{\circ}$C and two metal point standards will be purchased. Metals under consideration are Cadmium (melting point 321.1°C) and Zinc (melting point 419.5°C), which both have an uncertainty of 0.03°C. Future plans are to purchase a Gallium Standard (melting point 85.6°F) for low temp calibrations. To measure the resistance a precision resistance bridge from L&N and an 8 1/2 digit digital volt meter from Hewlett Packard will be used.

A Fluke calibrator will also be used in the primary lab to calibrate our field measurement and source devices, as well as the voltage and current sensing portions of the Daytronic Data Logging System. The calibrator has the ability to calibrate digital volt meters up to 4 1/2 digits. Long term plans are to move this calibrator to the secondary lab and purchase equipment to calibrate it as well as the digital volt meters with greater than 4 1/2 digit capacity. A precision shunt box from Transcat has been purchased to calibrate the RTD sensing cards. A Hewlett Packard pulse generator will be used to calibrate the pulse counter and timer portion of the Data Logging System.

In the secondary lab a precision oil bath circulator with a controller range and accuracy of -20 to 200°C and ±0.005°C respectively will be used for temperature calibrations. For the higher temperatures, an L&N thermocouple calibration furnace with a copper equalizing block will be utilized. In both cases, the test RTD's will be calibrated over their intended range with the Standard RTD's. A Hewlett Packard 3497 data logger with a built in 5 1/2 digit digital volt meter will be used to collect the data and transfer it to the computer for analysis.

Pressure transmitter calibration stations will be set up in the secondary lab, each with a Hewlett Packard 5 1/2 digit digital volt meter and a 0.1 percent accuracy deadweight tester.

CONCLUSIONS

As mentioned earlier, the intent of this paper is to provide guidance in establishing or enhancing a performance testing program. The current state of the Santee Cooper performance testing program is used to provide examples in the application of various procedures, but the references mentioned should be reviewed for application to a specific power plant.

As instrumentation and data acquisition continue to improve, changes in a performance testing program should follow. We at Santee Cooper are continually evaluating new instrumentation and data acquisition equipment in an attempt to further increase the accuracy of our tests and decrease the time required for test completion. Eventually, we intend to develop a standard test procedure and limit changes made between tests. However, with continuing improvements in hardware and software and increasing requests for additional performance information, the time frame for completion of this final goal is well into the future.

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